Frequency Shift Telegraphy—Radio and Wire Applications*

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Frequency shift telegraphy is described and compared with amplitude modulation telegraphy under various conditions found in radio and wire transmission. Experimental data are given to demonstrate the influence of various design factors on the over-all performance under these conditions. It is shown that the most outstanding characteristic of the frequency shift method is its ability to accept large and rapid changes in signal amplitude. Frequency shift telegraphy thus proves to be of great advantage for use in the H.F. radio range. Frequency shift telegraphy also shows an advantage over amplitude modulation telegraphy with respect to noise. For applications where the level variations are small or slow the advantage of the frequency shift method over amplitude modulation is relatively small.

Introduction

During World War II, single-channel and multichannel frequency-shift radio telegraph systems proved of the utmost importance in providing the Allied Powers with a world-wide automatic printing telegraph network for handling with precision, secrecy and dispatch the unprecedented volume of traffic engendered by a war of global extent. It is expected that the next few years will witness a greatly expanded application of this method of operation by commercial telegraph companies and others interested in long distance telegraphy.

Frequency Shift carrier telegraphy (FS) may be applied to any carrier telegraph circuit, but, as will appear below, it provides particularly striking advantages in H.F. radio transmission. For some other radio frequency ranges and for wire line operation the conditions are such as to limit the advantages of the FS method. The main advantages of the FS over the AM method are a greater ability to accept rapid level changes, which results in better stability and lower distortion, and an improvement in signal-to-noise ratio, which permits a reduction in carrier amplitude. It is therefore of particular importance where automatic printing is desired over H.F. radio circuits. When it is necessary to transmit through very high noise levels, low speed AM signaling with aural reception of an audio beat note remains the superior method.

FS is a form of frequency modulation in which signaling is accomplished by shifting a constant amplitude carrier between two frequencies representing respectively the marking and spacing conditions of the telegraph code. Frequency variations in FS telegraphy correspond to amplitude variations in

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AM telegraphy (CW); thus the signal transitions in FS are represented by frequency-time transients, while in the AM case they are amplitude-time transients. Since AM telegraph is the more common system, a discussion of the FS method involves numerous comparisons between the two systems. The merits of a telegraph system must be judged on its ability to combat the various adverse conditions encountered in the transmission medium and in the terminal apparatus. In general these adverse conditions involve variations in amplitude, frequency, and phase of the signals and the presence of extraneous signals and noise.

In the course of the development of a number of FS radio teletypewriter systems, a large amount of information concerning the characteristics and design parameters of such equipment has been obtained. It is the purpose of this paper to abstract therefrom selected data which will furnish a step-by-step comparison of the FS and AM methods. Typical terminal arrangements are described and the effects of varying certain design factors are illustrated by experimental data. Although the material presented applies largely to H.F. radio telegraph, much of it is of a general nature and with proper interpretation applies to other frequency ranges and transmission mediums and to cases in which the telegraph modulated carrier may be a sub-carrier or one of several sub-carriers.

General Discussion

Sideband Energy Distribution

The difference between FS and AM signals as regards distribution of side-band amplitudes is illustrated by the following two equations for a carrier of frequency $\omega/2\pi$ modulated with unbiased square wave dots of frequence $\rho/2\pi$.

For AM (On-off) keyed carrier of unity amplitude[1]:—

$$
\begin{aligned}
e = 0.5 \cos \omega t &+ \frac{1}{\pi} [\cos (\omega + \rho)t + \cos (\omega - \rho)t] \\
&- \frac{1}{3\pi} [\cos (\omega + 3\rho)t + \cos (\omega - 3\rho)t] \\
&+ \frac{1}{5\pi} [\cos (\omega + 5\rho)t + \cos (\omega - 5\rho)t] \ldots \text{etc.} \qquad (1)
\end{aligned}
$$

For FS keyed carrier of unity amplitude[2]:—

$$
e = \frac{2m}{\pi} \left[\frac{1}{m^2} \sin \left(\frac{m\pi}{2} \right) \cos \omega t \right.
$$

$$+ \frac{1}{m^2 - 1^2} \cos\left(\frac{m\pi}{2}\right)(\cos(\omega - \rho)t - \cos(\omega + \rho)t)$$

$$- \frac{1}{m^2 - 2^2} \sin\left(\frac{m\pi}{2}\right)(\cos(\omega - 2\rho)t + \cos(\omega + 2\rho)t)$$

$$- \frac{1}{m^2 - 3^2} \cos\left(\frac{m\pi}{2}\right)(\cos(\omega - 3\rho)t - \cos(\omega + 3\rho)t)$$

$$+ \cdots\cdots\cdots\cdots\cdots\cdots \Bigg] \qquad (2)$$

where m is the deviation ratio $= \dfrac{\text{frequency shift}}{2 \times \text{signaling speed}}$.

Typical sideband amplitudes calculated from these formulas are shown in graphical form in Fig. 1. In the case of FS keying, the relative amplitudes of the sidebands vary considerably as the amount of frequency shift is changed. For miscellaneous signals these line spectra do not exist but they do indicate the general distribution of energy over the band for a given signaling speed.

Methods of Modulating the Carrier

In AM telegraphy the carrier is usually modulated by simply interrupting it for the spacing condition. This is sometimes referred to as "on-off" keying. For low power and low frequencies the carrier may be keyed directly by electrical contacts. A more universally applicable method is to use vacuum tubes or other nonlinear elements to effectively interrupt the carrier. In some cases it is practical to start and stop an oscillator source of carrier.

The usual radio telegraph transmitter consists of an oscillator followed by a number of cascaded stages of amplification and frequency multiplication arranged to reach the desired output frequency and power. For on-off keying the carrier is usually interrupted by suitably varying the plate or grid voltage of one or more of the stages.

There are two general methods of obtaining frequency modulation: (a) The frequency of an oscillator may be modulated directly by suitably varying the frequency-determining circuit, (b) the output of a constant-frequency oscillator may be shifted in phase at such rates of change as to produce indirectly the desired frequency variations. In the latter case the marking and spacing intervals of an FS signal would be formed by periods of constant rate of phase change versus time. Square wave reversals would therefore require a triangular shaped wave of phase versus time. Since the transmission of long periods of steady mark or space would therefore involve huge

phase swings, the modulator would have to be able to produce a steady phase rate of charge. A phase modulator capable of performing in this way while not producing undesirable phase discontinuities at the signal transitions becomes rather impractical. For this reason FS telegraphy usually utilizes the direct frequency modulation method. This may conveniently be accom-

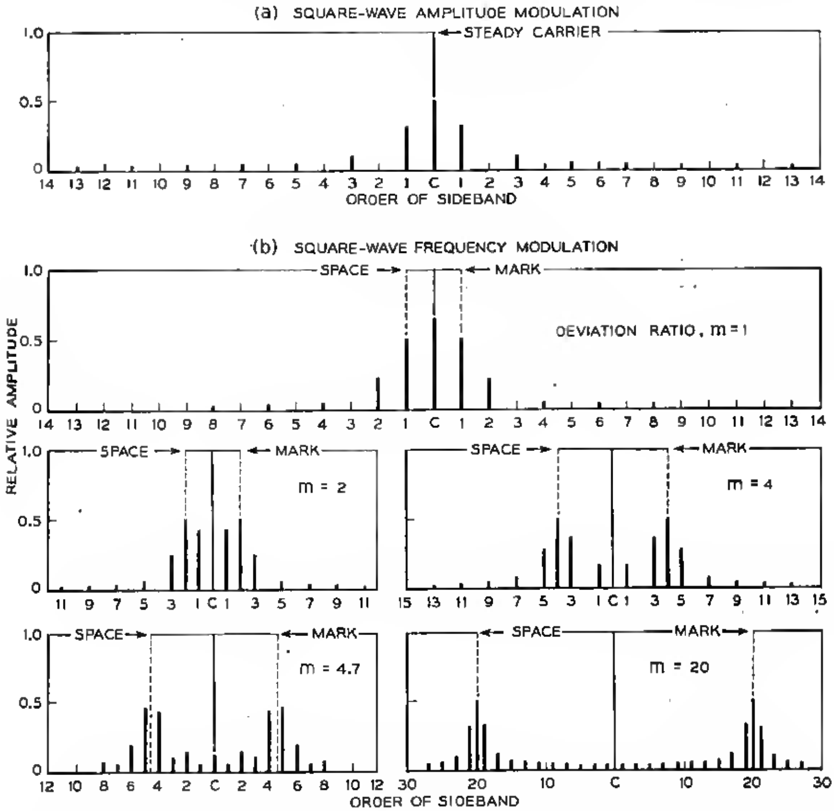

Fig. 1.—Amplitude of sideband components for (a) square-wave amplitude modulation (b) square-wave frequency modulation.

plished by the use of a reactance modulator which, by injecting a reactive component of current into the tuned circuit of the oscillator, varies the resonant frequency thereof. Such a modulator may be made linear so that a frequency shift proportional to the input voltage to the reactance modulator is obtained.

To apply FS telegraph signals to a radio transmitter the regular exciter oscillator is either replaced or modified by an arrangement providing a source of R.F. excitation that can be shifted in frequency in accordance

with the telegraph signal. All the stages are operated with full R.F. excitation continuously to produce a constant amplitude carrier.

As a matter of expediency frequency shift keying has sometimes been provided by switching between two independent sources of carrier current separated in frequency by the desired shift. In such a case the frequency transitions involve sudden phase discontinuities of random values. This results in the instantaneous frequency swinging considerably outside the steady-state mark and space frequencies. If the band is wide, such as is the case in a radio transmitter, there results a very broad sideband radiation capable of causing severe interference to adjacent channels. If the band is narrow, as might be the case where sending filters are employed, the interference is eliminated but the amplitude transients resulting from the sudden phase shifts are capable of producing considerable distortion.

Restriction of Transmitted Band

As seen above, square-wave modulation results in a wide spread of sideband components which are of sufficient amplitude to interfere seriously with adjacent channels unless greatly attenuated. The transmitted band may be restricted either by the use of a band-pass filter centered about the carrier frequency or by a low-pass filter to suitably shape the modulating wave form. Band-pass filters are usually used if the power level is low and the frequency low enough to permit suitable filter construction. For multichannel systems the use of band-pass filters also permits efficient paralleling of the transmitting channels. For radio transmitters with a transmitted power measured in kilowatts, and with a frequency of several megacycles which is frequently changed to suit best the prevailing conditions, shaping of the modulating wave is the more practical method of restricting the transmitted band.

Insufficient attention has been given in the past to the envelope shape of the signals from on-off keyed radio transmitters. With the ever increasing crowding of frequency assignments it becomes more and more important to restrict the emission of unnecessary sidebands arising from keying. The envelope shape in on-off keying may be controlled by properly shaping the modulating grid or plate voltage wave. It is important that the stages following the keyed stage or stages be nearly linear, otherwise the wave shaping will be largely destroyed. In the case of frequency shift keying, on the other hand, the wave shaping is preserved after passage through class C amplifier or multiplier stages, and these may be operated for maximum efficiency. The greater ease of producing and maintaining the desired wave shaping, so necessary for close frequency spacing of channels, is one of the outstanding advantages of frequency shift keying.

Apparatus

Typical FS Exciter for Radio Telegraph

A typical FS exciter arrangement such as is often used with radio telegrapb transmitters is shown in Fig. 2. A d-c. telegraph wave, after suitable sbaping, is caused to frequency-modulate an intermediate frequency of 200 kc. which, in turn, amplitude-modulates a radio frequency from a crystal-controlled oscillator. The upper sideband of this latter modulation is an FS signal and is selected and amplified sufficiently to drive the first amplifier or multiplier stage of the transmitter. The 200-kc. oscillator is frequency-modulated by a reactance modulator which, by feeding a leading or lagging

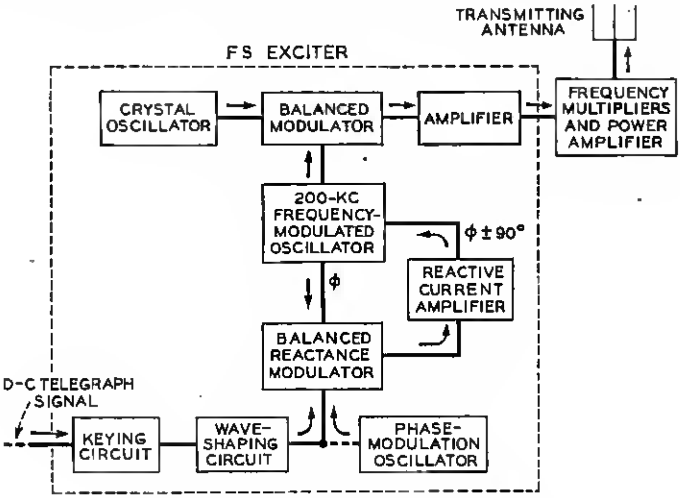

Fig. 2.—Block diagram of a typical FS transmitter.

quadrature component of current into the oscillator tuned circuit, decreases or increases the frequency. By operating the reactance modulator witbin its linear range the frequency shift wave form is made the same as tbe d-c. telegrapb wave form into the modulator. A d-c. amplifier stage, designated "keying circuit", is provided to furnish a modulating wave effectively isolated from amplitude and wave front variations of the incoming telegraph signals. The d-c. telegraph signals may be polar or neutral and are often obtained from a tone demodulator unit which allows keying from a remote point by V.F. telegraph. Tbe amount of frequency shift is adjusted by an amplitude control in the quadrature feed-back path to the 200 kc. oscillator. The shift may thus be varied continuously, or in definite steps to allow for subsequent frequency multiplications, by suitable attenuation controls. Controlling the shift in tbis manner keeps the instabilities of the reactance

modulator a constant percentage of the frequency shift, which would not be the case if the shift were adjusted by varying the amplitude of the modulating wave. The use of a balanced instead of an unbalanced reactance modulator minimizes variation of the mean frequency and also allows the shift to be varied without affecting the mean frequency.

The frequency-shift signal transitions are wave-shaped, to restrict sideband radiation, by means of a low-pass filter in the d-c. telegraph signal path to the reactance modulator. The low-pass filtering is made adjustable to accommodate a range of signaling speeds. Frequency-versus-time wave

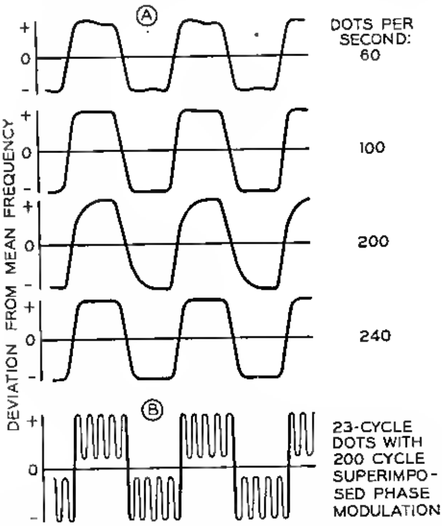

Fig. 3.—Frequency shift keyer output wave forms. (a) Low-pass filtering adjusted to produce similar wave shapes at dotting speeds of 60, 100, 200, and 240 cycles. (b) 200 cycle phase modulation superimposed on a 23 dots per second signal.

forms from an exciter of the type described are shown for several keying speeds in Fig. 3a. The effect of wave shaping on the sideband components in the R.F. output of such an exciter is shown in Fig. 4.

Phase modulation may readily be added to the signal in this type of exciter by superimposing the desired sine wave modulating frequency on the telegraph signal wave input to the reactance modulator as indicated in Fig. 2. Figure 3b shows the keyer output wave form with superimposed phase modulation. The use of this type of phase modulation is considered later.

To obtain optimum results in FS radio telegraph transmission and to allow close spacing of channels, a high degree of frequency stability is necessary. An over-all frequency stability of ± 100 cycles is desirable in a system using a value of frequency shift between 500 and 1000 cycles. A frequency

shift exciter of the type described above, with the crystal oscillator and 200 kc. FS oscillator located in a temperature-controlled oven, usually has a frequency stability such that the mean R.F. carrier frequency may be held to within ±50 cycles up to frequencies of 20 mc over ordinary periods of operation on any one frequency. One of the advantages of this type of exciter is tbat small inaccuracies in crystal frequencies may be compensated for by adjusting the mean frequency of the 200 kc. oscillator.

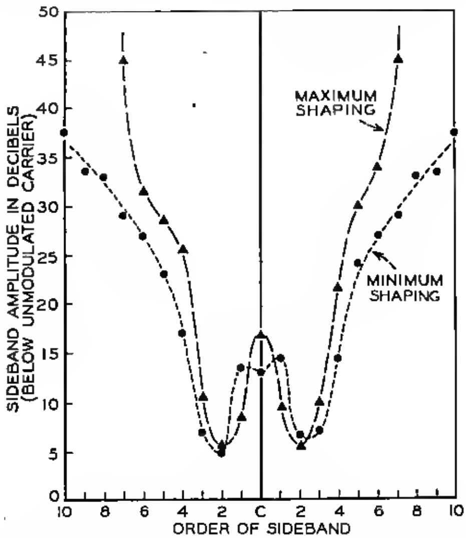

Fig. 4.—Effect of shaping FS transitions on amplitude of radiated sidebands. 100 dots per second and 500 cycle frequency shift. The maximum and minimum wave shaping conditions correspond to those used with 60 and 240 dots per second respectively in Fig. 3(a).

Receiving Terminal Arrangements

Typical receiving terminal arrangements are shown in the block diagrams of Fig. 5. Up to point "a" in the arrangements the FS and AM systems are identical, being of the usual H.F. superheterodyne type. The output from the second frequency-conversion stage may be either in the audio range or at a considerably higher frequency such as 50 kc. Following the second converter is a band-pass filter (shown at "b" in Fig. 5) which determines the final over-all band width before demodulation. The two systems differ only in the method of demodulation. The AM (on-off) signals are amplified and rectified to give a d-c.telegraph signal. The FS signals are amplitude limited and passed through a frequency discriminating network and then rectified to give a d-c.telegraph signal. Beyond this point the two systems are again identical. The d-c. signals pass through a low-pass filter to remove

carrier ripple and higher frequency noise components and are then amplified to a suitable level to operate automatic recording or printing apparatus. The d-c.signals may also be used to modulate an audio frequency so as to pass the signals to a remote point by multichannel voice-frequency carrier telegraph methods.

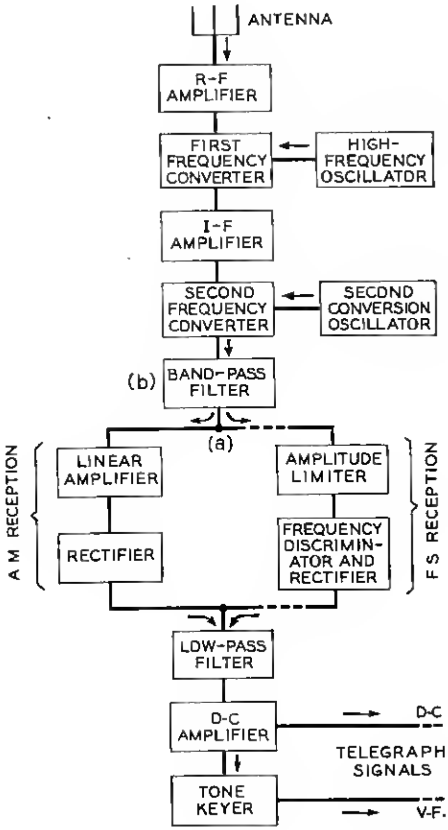

Fig. 5.—Block diagram of a typical receiving arrangement for either AM or FS telegraph signals.

The radio receiver portion of the terminals up to point "a" should be designed to have low noise and good selectivity. Extreme H.F. oscillator stability is necessary for either system if narrow band width operation is to be maintained without constant attention. An over-all frequency stability of ±50 cycles is desirable for the receiving terminal over a period of 6 to 8 hours. Sufficient selectivity and amplifier capacity should be provided at all points to prevent overloading by unwanted signals or loss of automatic

gain control. In the following discussion those portions of the terminals beyond the second frequency converter will be given major attention.

Experimental Transmitting and Receiving Arrangements

For the laboratory transmission studies described in the following sections the transmitter and receiver were located nearby and connected together by means of an amplitude modulator and associated with various sources of noise designed to simulate quantitatively and under controlled conditions the variations which would be encountered in the actual medium.

Throughout the tests 7.42 unit start-stop signals were used unless otherwise stated, and the speed was 60 words per minute (23 dots per second). Their peak distortion and bias were measured on a cathode-ray tube telegraph distortion measuring set.

An exciter of the type shown in Fig. 2 was used as a source of signals. A frequency of 6.4 mc. was employed, with the radio receiver connected to the exciter output through an amplitude modulator. This modulator was an electronic circuit permitting amplitude modulation of a frequency-shift signal to produce unequal mark and space amplitudes. This modulator was also used to amplitude-modulate a single frequency for the AM portions of the measurements.

A temperature-limited diode together with a two-stage tuned amplifier was used as a source of thermal noise centered around 6.4 mc. A polar relay driven by 60-cycle a-c and arranged to produce sharp polar impulses from the discharge of small capacitances connected to its contacts was used as a source of impulse noise. The noise level was adjusted by an attenuator and mixed with the 6.4 mc. carrier of the exciter. A minimum amount of wave shaping was used, so that the modulation may be considered as having been essentially square-wave.

Receiving Arrangements

The experimental data submitted in the following discussion was obtained from reception through a laboratory setup essentially like that shown in Fig. 5. The radio receiver proper was a commercial type of H.F. superheterodyne. The output of the second frequency converter was in the audio-frequency range, which enabled the use of various band-pass filters at "b" of the type used in voice-frequency telegraph systems. The amplitude limiter was effective over an imput range of -60 dbm* to above $+20$ dbm. The pass-band characteristics of the radio receiver and of the several band-pass filters used in position "b" are shown in Figs. 6 and 7 respectively. Unless otherwise stated, the frequency shift signals were centered about

* The symbol dbm signifies "db referred to one milliwatt".

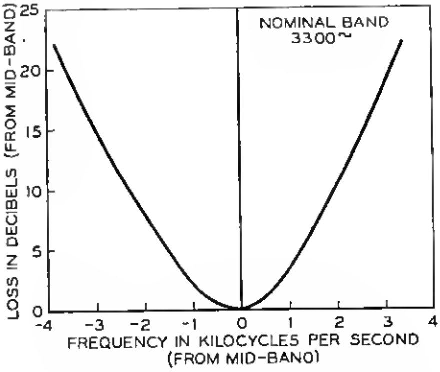

Fig. 6.—I.F. selectivity characteristic of radio receiver.

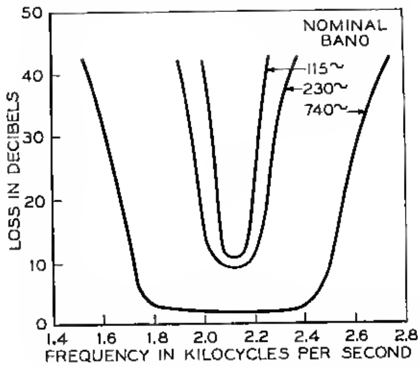

Fig. 7.—Attenuation versus frequency characteristics of bandpass filters shown at (b) in figure 5.

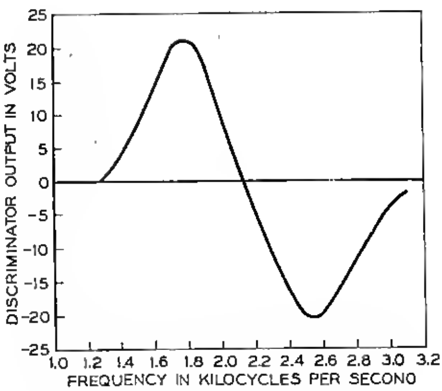

Fig. 8.—Linear discriminator characteristic.

2125 cycles and were demodulated by a linear discriminator centered about 2125 cycles as shown in Fig. 8. The characteristics of the low-pass filtering are shown in Fig. 9. These low-pass filters were adjusted by oscillographic observation of the signal wave form and had cut-off characteristics giving very little characteristic distortion[3]. The d-c. amplifier was a bigh-gain nonlinear type designed so as to bave a square-wave output having transitions established by the passage of the demodulated voltage wave tbrough a narrow amplitude range. The amplitude and wave front slope of the demodulated wave tbus had no effect on the output wave form and could not affect the distortion measuring equipment.

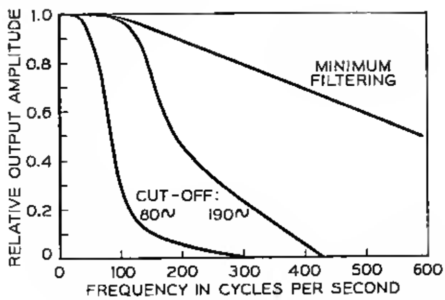

Fig. 9.—Attenuation versus frequency characteristics of low-pass filters.

Experimental Results

Band Width Before Demodulation

The band width before demodulation determines the amount of noise and interference which is to be accepted along with the desired signal and tbus largely determines the signal-to-noise condition at the antenna at wbich the system fails to receive intelligence. The band width at tbis point (point "a" in Fig. 5) also limits the signaling speed capabilities of the system. In the following experimental data the values of band width were measured hetween the points of 6 db loss ahove that at midband.

Effect on Signaling Speed

For both methods of signaling considered here the band width must be at least twice the maximum signaling speed in dot-cycles per second hut it is found that signal distortion rises rapidly for a hand width less than three times the maximum signaling speed, and that a factor of at least four times is indicated for a system which is to have reasonahly low distortion with any margin of safety. The signaling speed capability of a given band width is nearly the same for FS signals as for AM (on-off) signals. In Fig. 10 is

shown the over-all signaling frequency response to FS and AM signals for a nominal band width at point "a" of about 740 cycles. It will be noted that the FS method is but slightly inferior and that both systems fail at a frequency of approximately one-half the band width.

Effect on Noise:

The effect of *thermal noise* on distortion for bandwidths of 115, 230, and 740 cycles is shown in Figs. 11 and 12. The rms. noise-to-carrier ratios

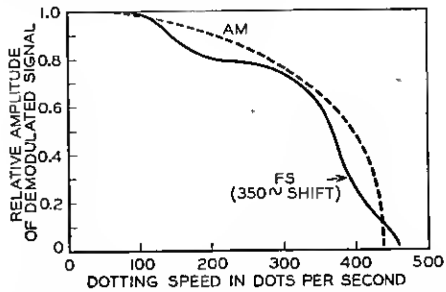

Fig. 10.—Overall frequency response of a 740-cycle band to AM and FS signals.

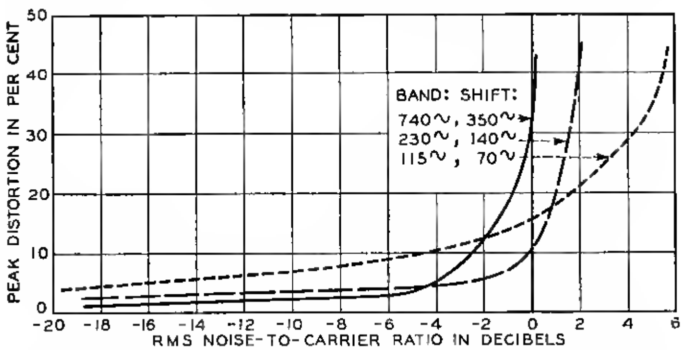

Fig. 11.—Peak distortion versus thermal noise for FS transmission—80-cycle cutoff low-pass filter.

indicated in the figures were measured in the 3300-cycle band of the radio receiver in all cases. The actual noise-to-carrier ratio existing in the transmission band used was lower and may be obtained from the following table. The values of correction are from rms. measurements.

Pass Band at Point "a"	Correction to be made
1920 cycles	−2.3 db
740	−6.5
230	−11.6
115	−14.3

For *AM signals*, Fig. 12, varying the bandwidth has little effect when the telegraph signal distortion is less tban 15%. Altbough tbe wider bands accepted more noise power, this added noise merely produced high-frequency noise components which were removed by the low-pass filter. This added noise does, however, cause the peak noise to exceed the signal amplitude at a lower noise-to-carrier ratio and cause failure before tbat for a narrower band condition.

In the case of *FS signals*, Fig. 11, changing tbe handwidth and the frequency shift simultaneously, and in approximately the same proportion, alters the whole distortion characteristic. At low noise levels a wider hand witb a greater frequency shift gives an improved signal-to-noise condition. However, as the noise level is increased the wider band causes the peak noise

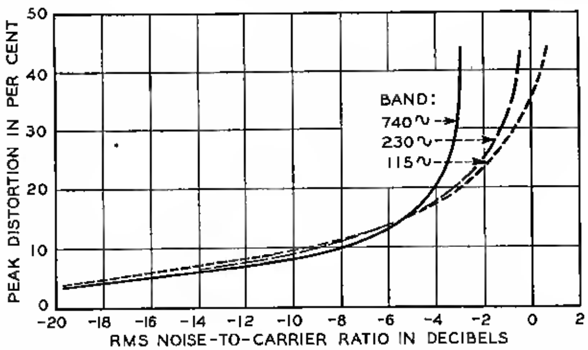

Fig. 12.—Peak distortion versus thermal noise for AM transmission—80-cycle cutoff low-pass filter.

to exceed the carrier at a lower noise level than with a narrower band. Thus a change to a wider band gives less distortion at low noise levels and more distortion at high noise levels. This results in a much more sharply breaking distortion characteristic for the wider band. This behavior is typical of frequency modulation systems in general.

Although the noise actually passed by the 740-cycle band filter was approximately 8 dh above that passed by tbe 115-cycle hand filter, the difference in the failure points (35–40% distortion) for the two bandwidths will he seen to be only ahout half tbis amount in dh for hoth AM and FS. This phenomenon is typical of carrier telegraph systems when compared at the same signaling speed. This means that it is not particularly beneficial to decrease hand width to obtain lower distortion under higb noise conditions. Tbe main reason for narrow bands is for more economical use of frequency space.

As to the *comparison between FS and AM*, the FS method has an advan-

tage of 2.5 to 4.5 db at a distortion of 35% to 40%, corresponding to the selector failure point of the usual teletypewriter. From a signal-to-noise standpoint it is thus seen that the gain in changing to the FS method is approximately equal to the resulting increase in average transmitted power of about 3 db. A comparison at a lower distortion such as 15% shows an advantage of 4 to 6 db. At a still lower distortion the 740-cycle band, because of the higher deviation ratio, shows an improvement of over 10 db. In this region the slopes of the curves make accurate comparisons impossible due to the masking effect of other sources of distortion. These large improvements at low noise levels are similar to those associated with wide-band FM broadcast systems. However, in carrier telegraph transmission the criteria are so different that the difference between a nearly perfect

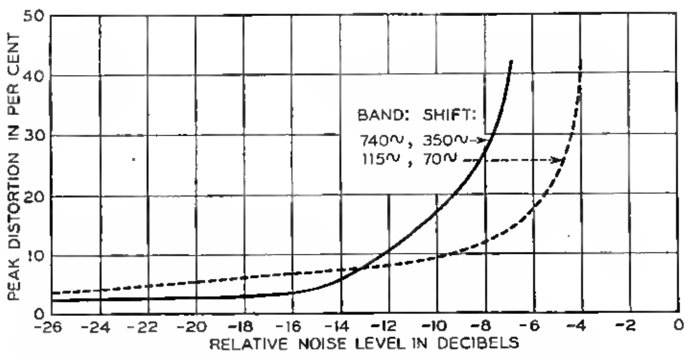

Fig. 13.—Peak distortion versus impulse noise for FS transmission—80-cycle cutoff low-pass filter.

circuit and one of small distortion is not of great importance except when a large number of telegraph sections are to be operated in tandem. From a practical standpoint the improvement in signal-to-noise is not more than about 6 db for equal band widths.

In Figs. 13 and 14 similar characteristics are shown for the case of *impulse noise*. The noise level values of these curves are purely relative since no attempt to measure the peak noise was made. The comparisons between AM and FS, and between different band widths, agree closely with those for thermal noise.

Effect of Limiter on Signal-to-Noise Ratio

The limiter in the FS system is a high-gain nonlinear amplifier which delivers to the frequency discriminating networks an essentially square wave having transitions coinciding with the passage of the instantaneous voltage of the input carrier signal through zero. The limiter thus passes only the

frequency or phase changes of the signal. Noise voltages which are small compared to the signal cause approximately linear phase modulation of the signal and this is passed through the limiter. The amount of frequency deviation thus imparted to the carrier by a given component of noise is proportional not only to its amplitude but also to its frequency separation from the carrier. This gives rise to the so-called "triangular noise spec-

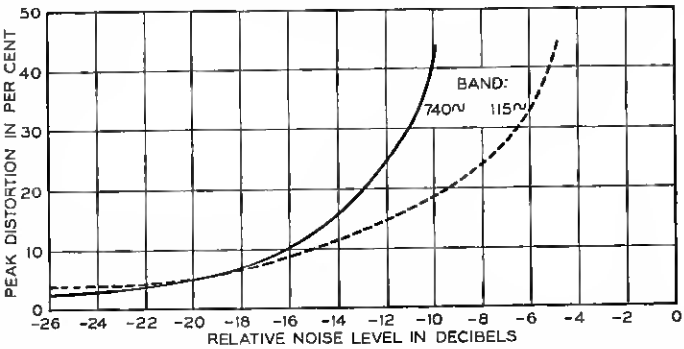

Fig. 14.—Peak distortion versus impulse noise for AM transmission—80-cycle cutoff low-pass filter.

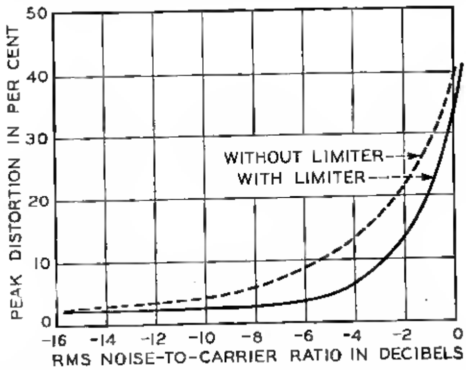

Fig. 15.—Effect of the limiter on distortion versus thermal noise for FS transmission—740-cycle band, 350-cycle frequency shift, 80-cycle cutoff low-pass filter.

trum"[4] when a linear frequency discriminator is used. If the limiter is removed from the frequency-shift terminal the noise components in phase with the carrier as well as those in quadrature therewith are allowed to reach the frequency discriminating network. For a balanced type discriminator this increases the demodulated noise for small amounts of noise about 3 db. In Fig. 15 is shown the effect of removing the limiter from the circuit. The limiter is seen to have little effect on the failure point, but an improvement of 2 to 4 db is shown in the 5 to 12% distortion region.

Other beneficial effects resulting from the use of a limiter are discussed below under "Level Variations".

Demodulation of Frequency Shift Signals

It is desirable that the frequency discriminating network be of the balanced type having two branches allowing differential combination of the two rectified outputs. This minimizes the response to amplitude modulation not eliminated by the limiter. Two general types of networks have been in common use for FS telegraph. One consists of two bandpass filters centered about the mark and space frequencies respectively and effectively dividing the total band into halves. The other consists of a two-branch network each branch of which has a varying amplitude characteristic extend-

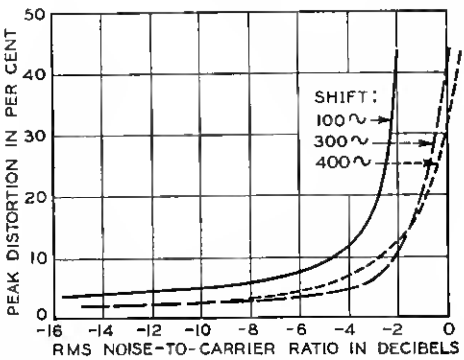

Fig. 16.—Effect of magnitude of frequency shift on distortion versus thermal noise in FS transmission—740-cycle band and 80-cycle cutoff low-pass filter.

ing over the complete transmission band and usually well beyond. The amplitude-versus-frequency characteristics of these two branches have opposite slopes and are of such shape that differential combination of their rectified outputs results in an approximately linear voltage-versus-frequency curve, passing through zero at midband. (Fig. 8)

In Fig. 17 is shown the characteristic of a two-bandpass-filter type of discriminator which was used in early frequency shift terminals. The characteristic is fairly flat near the mark and space frequencies so that this type of discriminator does not produce a triangular noise spectrum. In Fig. 18 is shown the type of discriminator characteristic obtained by the use of two narrow bandpass filters. In this case there is no broad flat region around the mark and space frequencies and an intermediate type of characteristic (approaching the linear type) is obtained.

With the linear type of discriminator the demodulated noise has the well known triangular spectrum and, as illustrated previously, the signaling

speed capability is essentially the same as an AM system of equal band width.

To compare experimentally these two general types of discriminators a 740-cycle band system with linear discriminator and 350-cycle shift was

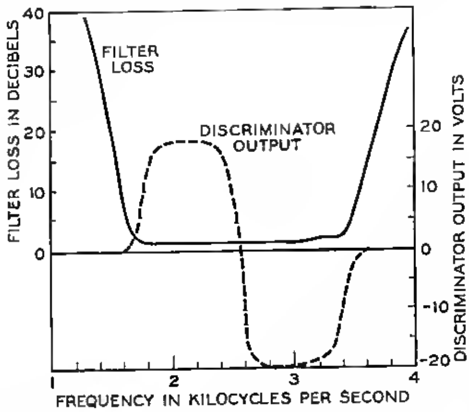

Fig. 17.—Characteristics of 1920-cycle bandpass filter and associated discriminator consisting of two bandpass filters.

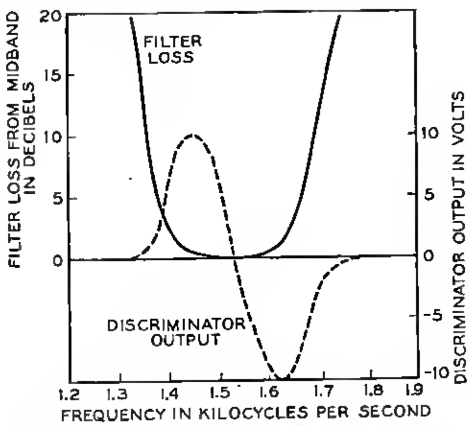

Fig. 18.—Characteristics of 295-cycle bandpass filter and associated discriminator consisting of two bandpass filters.

compared with a system with a bandwidth of about 1900 cycles, a discriminator consisting of two 740-cycle bandpass filters, and an 850-cycle shift. The results are shown in Fig. 19. The two systems are seen to reach failure distortion values at the same signal-to-noise point, with the linear discriminator becoming about 3 db superior at distortions around 5%. A second comparison was made using roughly equal bandwidths. A 295-cycle

band with a discriminator consisting of two bandpass filters and 170-cycle shift was compared with a 230-cycle band with a linear discriminator and a shift of 140 cycles. The results are shown in Fig. 20. The linear discriminator in this case appears to fail slightly sooner but shows a superiority of about 2 db in the 5% distortion region. Due to the rounded character-

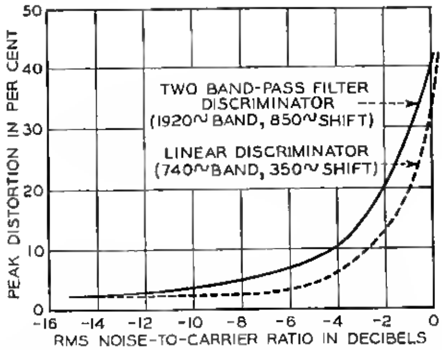

Fig. 19.—Linear discriminator versus two-bandpass-filter discriminator having the same signaling speed capability. Effect of thermal noise on peak distortion—80-cycle cutoff low-pass filter.

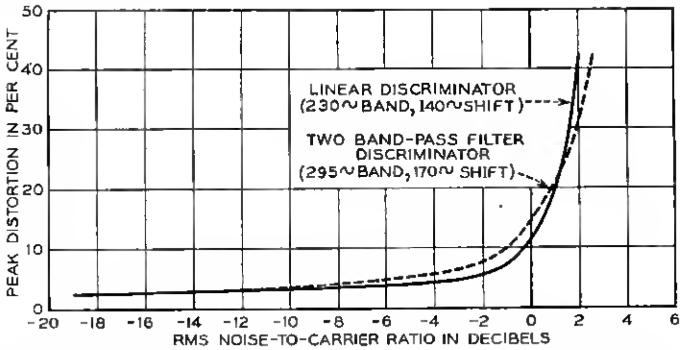

Fig. 20.—Linear discriminator versus two-bandpass-filter discriminator with equal bandwidths. Effect of thermal noise on peak distortion—80-cycle low-pass filter.

istic of the two bandpass filters used as a discriminator in the second comparison (Fig. 18) the difference in discriminators is less than in the previous test. It has been found[5] that for *a given signaling speed* capability almost twice the bandwidth is required if a two-bandpass-filter discriminator is used instead of the linear type. This added band width does not appear to cause any loss in signal-to-noise capabilities as to the failure point. The less sharp breaking point, however, makes the linear discriminator superior for moder-

ate and low distortions. For a system occupying *a given bandwidth* the two-handpass-filter discriminator provides some improvement at the failure point but is still somewhat inferior to the linear discriminator at moderate distortions. More importantly the two-handpass-filter discriminator impairs the signaling speed capabilities to an extent which depends upon the shape of the cutoff of the filters used.

Bandwidth After Demodulation (Low-Pass Filtering)

In an *Am system* the low-pass filtering after demodulation can, to a large degree, make up for a greater than necessary bandwidth before demodulation. During *marking intervals* the added noise admitted by a wide hand causes noise in the demodulated output at frequencies higher than the signaling frequency and this can be filtered out, unless the noise is so great as to over-modulate the carrier. During *spacing intervals* there is no carrier and hence only the noise is rectified. Added noise admitted hy a wide hand causes not only higher-frequency components in this rectified noise, which may he filtered out, but also an increase in the d-c. component. This tends to cause marking bias of the received signals as the noise level increases.

In an *FS system*, where the carrier is present continuously, the added noise from a wider hand produces high-frequency noise components in the demodulated output which can he filtered out by the low-pass filter if the noise level is low. As the noise level increases there are short intervals when the noise envelope exceeds the carrier. The action of the limiter is to give preference to the greater signal, in this case the noise, and since the noise will appear to the discriminator as a carrier fluctuating around midhand as a center, the demodulated output momentarily dips toward zero. As the noise increases, the duration and frequency of these holes in the signal increase. The low-pass filter, hy excluding frequencies considerably in excess of the maximum signaling speed, prevents these holes in the signal from producing false or extra transitions in the telegraph signal output. The low-pass filtering, however, cannot prevent the true transitions from heing displaced by this type of noise component since the signal is ohliterated momentarily. Its most important function is to prevent a hreakup in the signal output until a fairly high distortion is reached. For noise peaks exceeding the carrier the low-pass filter of an AM system also serves much the same purposes.

In Fig. 21 is shown the effect of changing the handwidth of the low-pass filter in an FS and in an AM system in the presence of thermal noise. The effect of a narrower low-pass filter is seen to consist mainly in shifting the breaking point toward a higher noise level. Similar characteristics for the case of impulse noise are shown in Fig. 22.

Magnitude of Frequency Shift in Relation to Bandwidth

A frequency-shift transient in a band of given width has a wave shape much like that of an amplitude transient in the same band provided the sbift is symmetrical and not over 50% of the bandwidth.[6] If the frequency shift approaches the total width of the band the transient is of such shape as to

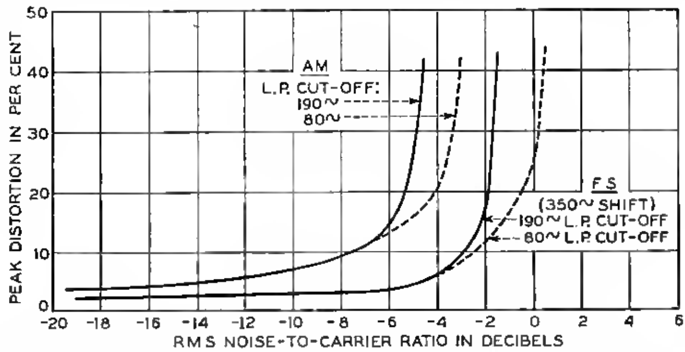

Fig. 21.—Effect of the low-pass filter cutoff frequency on distortion in the presence of thermal noise—740-cycle band.

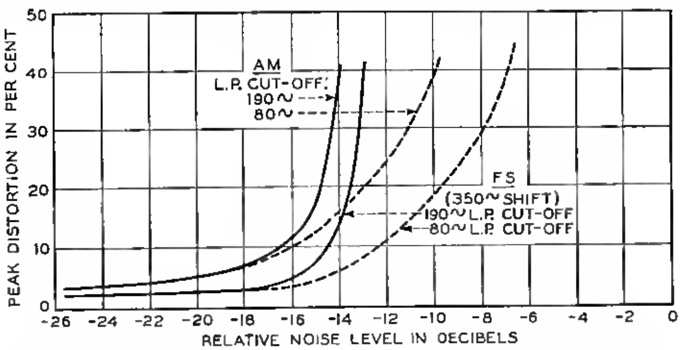

Fig. 22.—Effect of the low-pass filter cutoff frequency on distortion in the presence of impulse noise—740-cycle band.

cause distortion and to make the system more susceptible to noise. A very small shift results in a low amplitude of demodulated signal, which is more readily distorted by noise and biased by frequency drifts. It is of interest, however, that the signal-to-noise ratio of the demodulated signal is not proportional to frequency shift for high noise conditions. As described before, noise peaks tend to reduce momentarily to zero the output from a balanced discriminator. The amplitudes of the dips or boles are thus about one-half tbe demodulated signal amplitude for any value of shift. This tends to maintain a constant signal-to-noise condition and this characteristic

is illustrated by Fig. 16 in which the breaking point with a 100-cycle shift occurs only 2 db before that with a 400-cycle shift although the difference in actual signal amplitude is 12 db. Figure 23 shows the effect on signal-to-noise ratio of progressively varying the frequency shift while the bandwidth

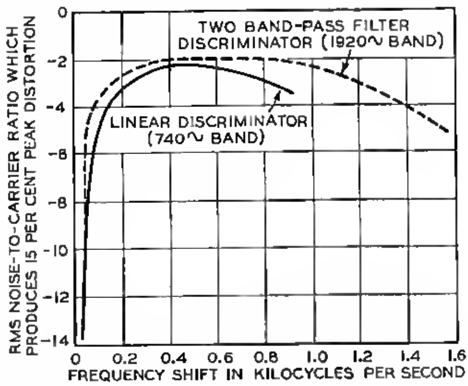

Fig. 23.—Effect of magnitude of frequency shift on distortion produced by thermal noise—80-cycle cutoff low-pass filter.

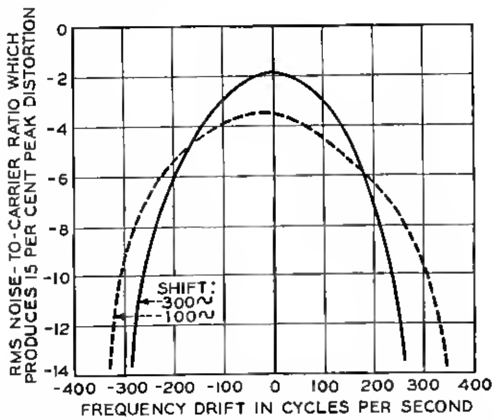

Fig. 24.—Effect of frequency drift on distortion produced by thermal noise in FS transmission—740-cycle band and 80-cycle cutoff low-pass filter.

is kept constant. There is a fairly broad region in which the signal-to-noise ratio is little affected by the amount of frequency shift. For optimum results a frequency shift of 50% to 60% of the band width is indicated, and thus has been used in most of the experimental results given herein.

Frequency Instabilities

Frequency drift of the carrier input to the receiving terminal in general causes biased signals and if severe enough results in failure of the system.

In Fig. 25 is shown the effect of frequency drift on signal bias in an *AM system.* In an AM system little bias is produced until the carrier reaches the cutoff region of the filter. The bias then becomes rapidly negative due to the increased loss and decreased amplitude of demodulated signal. When an automatic gain control arrangement is used the bias becomes positive due to a distorted envelope shape. The demodulated wave form determines the degree of sensitivity to frequency drift and depends on the bandwidth both before and after demodulation.

In an *FS System* using a linear discriminator, frequency drift changes the d-c. component of the signals and thus changes the operating point on the demodulated wave. The amount of bias depends upon the slope of the wave front and is thus affected by the amount of low-pass filtering. The effect of frequency drift on bias for a number of FS systems is shown in Figs. 26 and 27. If a two-bandpass filter type of discriminator is used the system

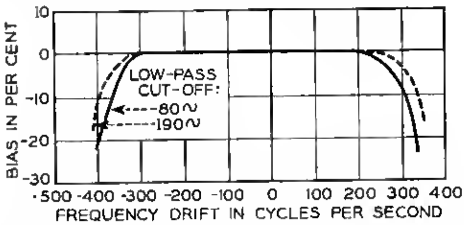

Fig. 25.—Signal bias versus frequency drift for AM transmission in a 740-cycle band.

is insensitive to moderate frequency drifts due to the flat pass bands as illustrated in Fig. 26. The relative shape and amplitude of the signal from a linear discriminator does not change appreciably with frequency drift; only a d-c. displacement occurs. This makes it desirable to have the low-pass filter coupled to the output amplifier by a network which passes only the useful signaling frequencies and blocks the d-c. and very slow drift components. When this is done the effect of frequency drift on bias is not greatly different from that for an AM system, as may be seen by comparing the dotted curves on Figs. 26 and 27 with Fig. 25.

The general method of performing this d-c. elimination is illustrated in the block diagram of Fig. 29. The output from the low-pass filter is passed through a coupling network which blocks the d-c. and passes the useful signaling frequencies. The output of the coupling network is passed through a positive feedback nonlinear amplifier which has but two output conditions representing the mark and space of the telegraph signal. The feedback network passes d-c. and low frequencies so as to just compensate for the loss of the coupling network. The time constant of the coupling network may be made large enough so that the signal wave form into the

d-c. amplifier is practically the same as at the output of the low-pass filter. The operating point on the demodulated wave may be readily adjusted by

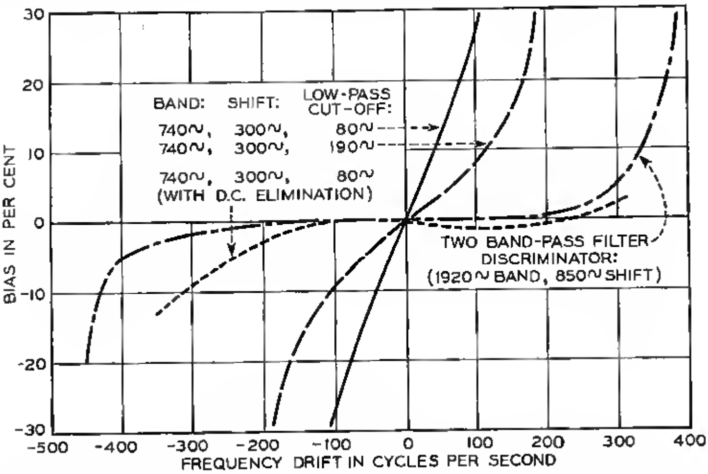

Fig. 26.—Signal bias versus frequency drift for FS transmission—wide filter bands.

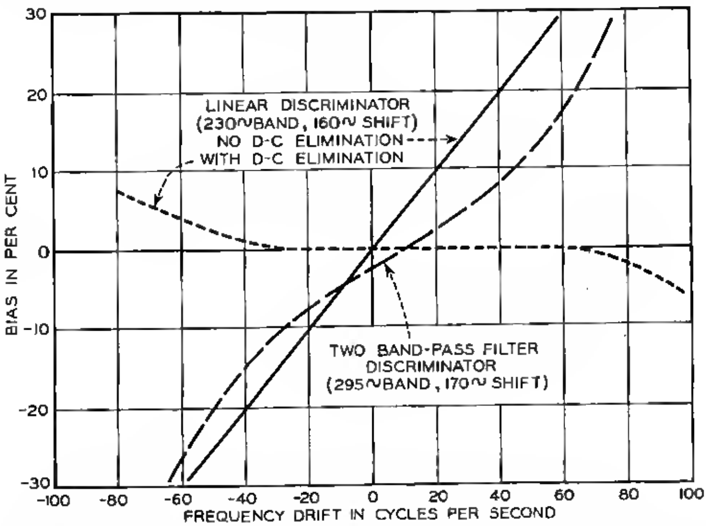

Fig. 27.—Signal bias versus frequency drift for FS transmission—narrow filter bands.

adjusting the bias voltage at the input to the d-c. amplifier. This arrangement differs from the impulse type of d-c. elimination, in which the demodulated wave form is effectively differentiated to form pulses but a fraction of a unit dot in length.

When d-c. elimination is used, operation with FS signals decentered in the pass band causes little bias but it does cause a loss in signal-to-noise ratio, especially at high noise levels. Due to the effect of noise peaks in causing a dip toward zero in the demodulator output, the effect of noise becomes exaggerated during the signal condition which is farther from midband. This change in signal-to-noise condition with frequency drift is shown in

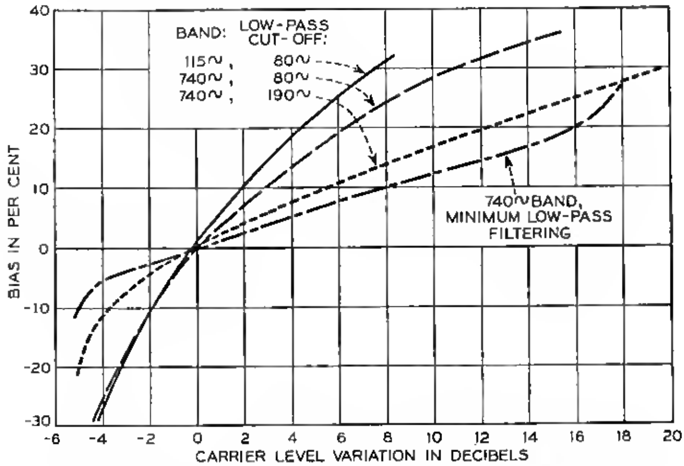

Fig. 28.—Signal bias versus carrier level variation for AM transmission.

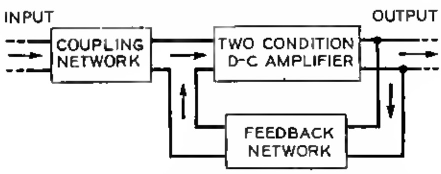

Fig. 29.—Block diagram of dc. elimination and restoration method used to minimize signal bias caused by frequency drift.

Figs. 24 and 30. A comparison between a two-bandpass-filter discriminator and a linear discriminator with d-c. elimination as regards frequency drifts in the presence of noise is shown in Fig. 31.

Radio telegraph systems operating in the H.F. region require a high degree of frequency stability if narrow bandwidths are to be used. Because of the several frequency conversions involved a number of different oscillators or frequency sources are involved but usually the major burden of frequency stability rests on the transmitter exciter and the high-frequency beating oscillator of the receiver.

Various methods of automatic frequency control may be used to hold the

carrier input to the demodulator at the correct frequency. In the case of FS signals the control may be arranged to operate only on the marking frequency or to utilize both the mark and space conditions. It is preferable to have inherent frequency stability rather than to compensate for the drift at the receiving end since it is difficult if not impossible to provide an automatic frequency control which will not reduce the transmission capabilities

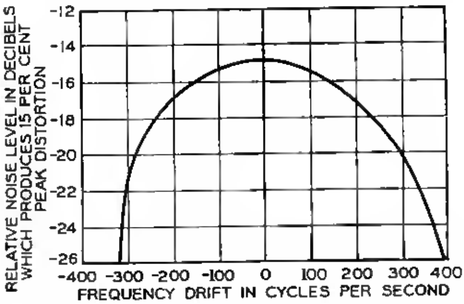

Fig. 30.—Effect of frequency drift on distortion produced by impulse noise in FS transmission—740-cycle band, 100 cycle frequency shift, 80-cycle cutoff low-pass filter.

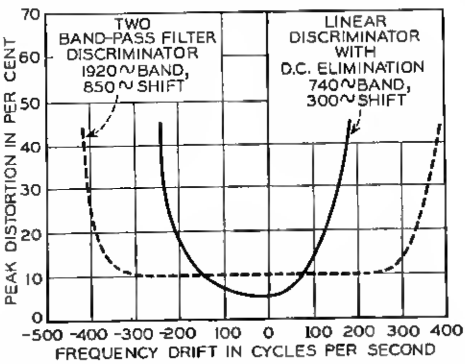

Fig. 31.—Linear discriminator versus two-bandpass-filter discriminator when frequency drift occurs in the presence of thermal noise—–4 db rms noise-to-carrier ratio.

of the system in the presence of noise and other interference. Best results are obtained if the frequency stability is high enough to require but a very slow correction, which usually dictates some mechanical rather than electronic tuning arrangement. Manual retuning may be found satisfactory where stability is reasonably good provided care is taken in making the adjustments. Suitable frequency stability with the retention of flexibility in frequency adjustment may be obtained by frequency sources making use of a combination of crystal oscillators and high-stability variable oscillators of lower frequency.

Level Variations

Extreme and rapid variations of received level exist in H.F. radio transmission. It is upon the ability to accommodate these level variations that the merits of an H.F. radio telegraph system must largely be judged. FS telegraph shows its outstanding advantage in this respect.

In an *AM system* in order to obtain zero-bias signals and optimum signal-to-noise conditions the operating point must be near the half amplitude point on the demodulated wave. This means that complete failure will result for a drop in level of 6 db unless some compensating arrangement is provided. The slope of the bias-versus-level characteristic depends upon the slope of the demodulated wave which in turn depends on the bandwidth of the system and upon the degree of low-pass filtering. The bias-versus-level characteristics of some AM systems are shown in Fig. 28. Where the level variations are relatively slow compared to the signaling speed, automatic gain control circuits can be used to maintain a nearly constant level into the demodulator. However, where large rapid level changes occur, as in the H.F. range, it is seen that a narrow band AM system would fail completely regardless of the amount of transmitted power. For printer operation over an AM system in the H.F. range a fairly wide band and little low-pass filtering should be used, so as to keep the wave shape of the signals as square as possible and thus obtain a fairly flat bias-versus-level characteristic. By adjusting the operating point low on the demodulated wave, approaching the spacing noise level, the greatest possible range of acceptable rapid level change will be obtained. The slower level change components may be handled by the usual automatic gain-control circuits. This will cause the bias of the signals to average somewhat marking but the peak distortions will be kept to a minimum.

In an *FS system* no bias is produced so long as both the marking and spacing frequencies are affected alike, with their received levels remaining equal. Such non-selective fading conditions cause no distortion even when they occur at quite rapid rates. If a balanced type of discriminator is used, amplitude limiting is not essential to obtaining this immunity from non-selective variations in attenuation. It is only when the mark and space levels are different that bias results. In Fig. 32 are shown bias versus mark-to-space level ratio characteristics both with and without a limiter. More bias exists when there is no limiter because the amplitude of the demodulated wave is directly affected and consequently the low-pass filtering also becomes a factor. With a limiter the amplitude of the demodulated wave is held constant and the amount of low-pass filtering has no effect on bias. Some bias is still produced, however, due to the differently shaped frequency transients in the passband of the receiving system when a level change occurs

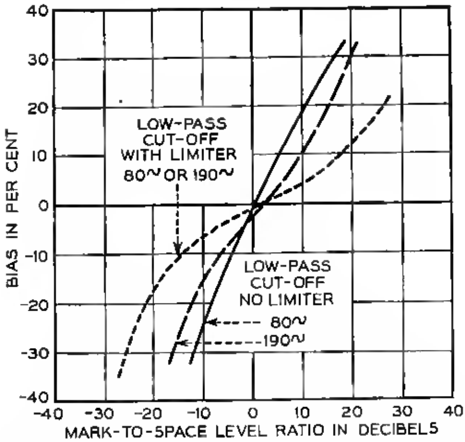

Fig. 32.—Signal bias versus mark-to-space level ratio in FS transmission—740-cycle band, 350-cycle frequency shift.

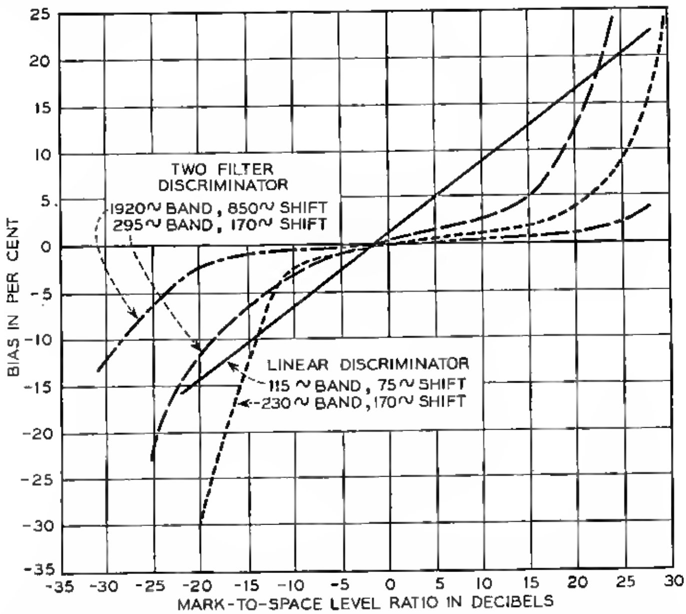

Fig. 33.—Signal bias versus mark-to-space level ratio in FS transmission—80-cycle cutoff low-pass filter.

at the moment when the frequency changes. In Fig. 33 this bias effect is demonstrated for various bandwidths. For moderate mark-to-space level ratios the bias effect is small and linear, with a slope which usually varies

inversely with a change in bandwidth. At extreme level differentials the bias may rise very rapidly due to the amplitude and phase characteristics of the input passband; transients from the greater amplitude condition may severely interfere with the lower amplitude condition. For the types of bandpass filters used in the tests it appeared that the amount of level difference required to produce 20% bias did not change greatly with bandwidth. Severe wave shaping of the signal at the transmitter was found to be an aid in reducing the bias effect due to such transients but the characteristic distortion became too great to give any practical improvement.

The fading modulator used in obtaining the data for Fig. 33 caused no change in phase. Selective fading over an actual radio circuit would involve considerable phase shift and greater distortion might be expected. The data of Fig. 32 were obtained by use of the phase control associated with the crystal filter of the radio receiver to vary the loss-versus-frequency characteristics of the receiving pass band and thus cause unequal mark and space amplitudes. This method gave an amplitude and phase characteristic for the transmission band more like that over an actual radio circuit.

Multipath Propagation Effects

The rapid fading conditions prevailing in the H.F. range are brought about by multipath propagation. Under such conditions, the signal induced in a receiving antenna by a distant transmitter may be the resultant of two or three separate waves each propagated over a different path. If two waves arrive over paths differing in length by an odd number of half wavelengths the resulting 180° phase difference causes maximum cancellation. On the other hand if the paths differ in length by an integral multiple of whole wavelengths the waves arrive in-phase and maximum reinforcement results. The difference in path lengths may at times be as great as 500 to 1500 kilometers (delay times of 2 to 5 milliseconds) which in the H.F. region corresponds to thousands of wavelengths. Under these maximum conditions waves at one frequency may arrive in phase while waves at a frequency a few hundred cycles away may arrive in phase opposition. Since the path lengths are constantly changing, the transmission at a given frequency is subject to wide variations in amplitude and phase with time. When the difference in path lengths is not great enough to cause frequencies in one portion of a communication channel to fade differently from those in another portion the term "non-selective" or "flat" fading is applied. When the difference in path lengths becomes great enough to cause considerable amplitude or phase distortion over the transmission band the term "selective" fading is used. Since the propagation paths existing at a given moment vary for different antenna sites, the fading patterns obtained from two or three antennas separated by several wavelengths usually show a

considerable phase difference so that a given frequency is not likely to fade into the noise level at all antennas simultaneously. By employing separate receivers for each antenna and suitably combining or selecting the demodulated outputs, a system is obtained which is much less susceptible to fading. Such a method is called *space diversity* reception. Inasmuch as fading over a given combination of paths is highly selective with respect to frequency much the same effect is obtained by *frequency diversity* reception. When this method is employed the intelligence is transmitted on two or more frequencies simultaneously and then received by separate receivers from a single antenna and the resulting demodulated signals combined or selected as for space diversity.

In telegraph transmission large differences in delay over two separate propagation paths cause the telegraph signal transitions to arrive at different instants over the two paths. Thus, there are intervals of overlap when a marking condition is received over one path and a spacing condition over a second path. When two components of nearly equal amplitude arrive at nearly 180° phase difference a signal transition may involve large and sudden amplitude and phase changes. The resulting transients in the bandpass networks of the receiving equipment may cause fortuitous distortions considerably greater than the difference in delay times over the two paths. The wider the pass band of the receiving system the shorter the duration of these fortuitous transients and hence the less the distortion. This phenomenon is one of the determining factors in the selection of bandwidth and frequency shift to be used in a given application of FS telegraphy. It becomes of increasing importance when the circuits are long and at higher signaling speeds such as are used in time-division multiplex methods.

In an AM system the effect of large differences in path lengths is usually a filling in of the spacing intervals with resulting marking bias. In an FS system the overlap time and associated transients may add to either marking or spacing intervals in a random fashion depending on the amplitude and phase conditions at each transition. The overlapping of the mark and space frequencies in FS transmission can sometimes be heard in an AM receiver as short pips of audio tone at each transition, the audio tone being the beat between the two frequencies.

Use of Superimposed Phase Modulation

Superimposed phase modulation has sometimes been employed as a simple means for achieving a certain amount of frequency diversity both in AM and FS telegraph systems. This consists in causing the radiated signal to oscillate continuously through a small phase angle at a rate relatively high compared to the dotting speed. Phase modulation spreads the energy of the signal over a wider frequency band so that the complete loss of the

signal through selective fading becomes less probable. The spectra generated by sinusoidal phase modulation of 1.0, 1.4, and 2.0 radians are shown in Fig. 34. Most of the energy is seen to be concentrated in the carrier and first order sidebands. Less than 1.0 radian of modulation results in too little amplitude of the sidebands, while more than 1.5 radians results in too wide spread of energy outside the first order sidebands. The center three

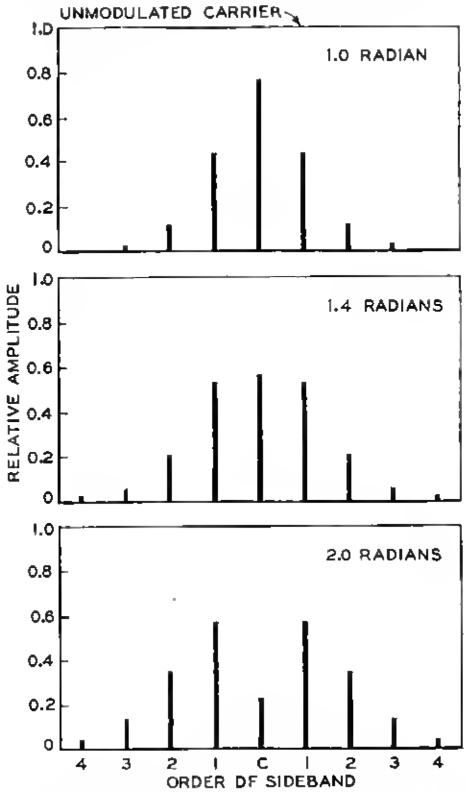

Fig. 34.—Frequency spectra for sinusoidal phase modulation.

components are equal at about 1.4 radians. In the case of FS the phase modulation frequency appears as a variation in amplitude of the signals from the discriminator. For AM no additional amplitude variation is caused by the phase modulation if there is no selective attenuation in the medium, but if such exists the phase modulation frequency or a multiple thereof appears in the rectified signal. To permit these unwanted amplitude variations to be removed by the low-pass filter so as not to break up the signals, the phase modulating frequency should preferably be ten or more times the maximum signaling frequency.

A test of superimposed phase modulation on FS signals was made over a radio circuit approximately 200 miles in length. A frequency shift of 850 cycles, and one radian of 200-cycle phase modulation, was used. A 60-word-per minute test sentence was transmitted and received without space diversity. It was found over a period of several hours that the phase modulation, on the average, gave a decrease in printed errors of about 50% when the error rate was in the proximity of 1 to 2%. For short intervals the reduction in errors was often considerably greater. The use of 200-cycle phase modulation when space diversity is used provides little or no improvement and is therefore undesirable.

A more effective way of employing phase modulation with FS signals would be to use a phase swing of ± 1.4 radians at a frequency of 2 to 3 times the frequency shift and to demodulate separately the three major components of the signal, thus obtaining in effect a triple-frequency diversity system. This of course involves quite a wide transmitted band, but it might be of use in cases where space diversity is impossible, such as on board ships. When a space diversity arrangement is feasible it is much to be preferred.

Diversity Operation

To obtain reliable operation in the H.F. range it is common practice to employ space diversity reception. The use of frequency diversity, with the increase of transmitted power and greater frequency space required, is seldom justified if space diversity reception can be arranged. For AM radio telegraph, double or triple-space diversity receiving arrangements are frequently used. Since an FS signal generally covers more frequency space, it is even more likely to be mutilated by selective fading than an AM signal. It has been found, however, that a double-space diversity system for FS signals usually gives sufficient diversity action provided it is of a type that permits switching between channels at signaling speed without causing appreciable distortion. This is necessary since it is a frequent occurrence that the mark of one channel may fade, leaving a good space, while the opposite may occur on the second channel. Since an FS system can accept rapid level changes, the main purpose of diversity methods is to insure that both the mark and space portions of the signal will be received above the noise level. In the case of AM telegraph, since it cannot accept rapid level changes, diversity operation is important not only in keeping the signal above the noise but also in averaging out some of the rapid level changes. For this reason AM systems usually show considerable improvement in going from double to triple diversity. It would be expected that a like change would show much less improvement in an FS system.

Diversity Channel Selection

The method employed to combine or select the channels of a diversity system is of great importance. For an AM system the relatively simple method of using a common load circuit for the diode detectors of the diversity channels is generally used. By deriving a common AVC voltage from the combined output and by properly adjusting the receiver sensitivities a fairly constant output is obtained. The parallel connection of the diode detectors causes the stronger signal to effectively block the weaker signal thus giving a fairly sharp diversity selection characteristic. The problem of combining the diversity channels of an FS system is more complicated mainly because of the amplitude limiting. If amplitude limiting is used in each diversity channel before demodulation, the resulting constant amplitude signals convey no information as to their relative amplitudes as received from the antennas. Any diversity selection must then be obtained by some indirect method. It is necessary to furnish some selecting device since the noise from a faded channel, if added directly to a good signal from another channel, will cause high distortion.

In an early frequency shift system employing a two-bandpass filter discriminator (shown previously in Fig. 17) it was found that for a poor signal-to-noise condition the sum of the outputs of the mark and space rectifiers increased above that for a good signal-to-noise condition. This increase was utilized to suppress the output of the poorer channel and emphasize that of the better channel. Although neither the degree of diversity selection nor the speed of response was as good as might be desired, fairly satisfactory results were obtained.

Another method which has been used involves the derivation of control currents or voltages proportional to the amplitudes of the incoming signals which in turn select the better diversity channel by some type of gate action. The time constants of the control circuits must be low enough to permit switching at signaling speed without introducing considerable distortion. The gate circuits must also be of a type which does not introduce interfering transients or otherwise allow the control voltages or currents to interfere with the signal. This method permits very sharp diversity selection and has the capability of approximating ideal results although it becomes somewhat involved in a practical form.

A considerably simpler method has been used in some of the more recent FS terminals. It is based on the use of a single-amplitude-limiter through which pass the signals of both diversity channels. This is made possible by arranging the two signals at the input to the limiter to be at different frequencies. At the output of the limiter the two signals are separately demodulated and then combined. When one of the signals is considerably

greater in amplitude than the other at the input to the limiter the relative difference in level is increased by an additional amount of about 6 db at the limiter output. The limiter output may be considered as the stronger signal frequency-modulated by the weaker signal. For small modulation indices the amplitude of the first order sideband is approximately one-half the modulation index thus explaining the 6 db added difference in level at the limiter output. As the input levels approach equality the added level difference decreases to zero. A block diagram indicating the arrangement of such a diversity system is shown in Fig. 35. Tests were made of both parallel and series connections of the two discriminator outputs. With a parallel connection the discriminator having the greater output blocks the rectifier output of the other discriminator and thus gives a sharp diversity selection characteristic. However, the level ratio of the channels at which a switch

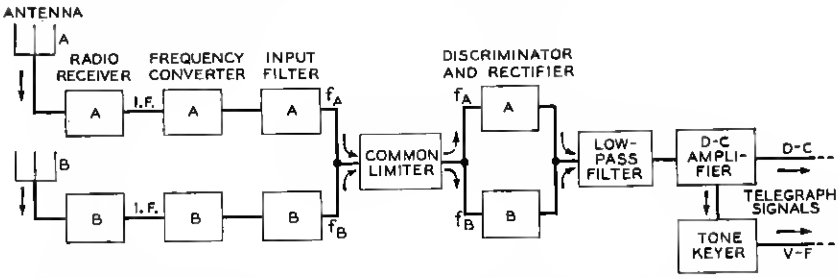

Fig. 35.—Block diagram of dual-diversity FS receiving system using a common limiter.

takes place is affected not only by the ratio at the limiter input but also by frequency drift and discriminator slope. With the series connection only the input level ratio at the limiter input affects the diversity switching; this arrangement was therefore selected as the preferred method although its selection characteristic is not sharp. The series and parallel combining characteristics are shown in Figs. 36 and 37.

Various tests were made on a terminal having a 1500-cycle bandwidth and using the series combining method to determine the signal-to-noise characteristics under different conditions of diversity fading. A frequency shift of 850 cycles was used and the midband frequencies of the two diversity channels at the common limiter input were 30 and 35 Kc. Figure 38 shows the distortion versus signal-to-noise ratio characteristics of each channel separately and in diversity combination for various relative level conditions of the two channels. During diversity operation equal noise levels were maintained in the two channels and various combinations of level differences of the two channels were preserved as the whole signal level combination was varied. The level differentials are indicated in

the figure for each curve. The signal-to-noise level scales refer to the highest level portion of the diversity signal. Since the amplitude modulator which was used to simulate the selective fading did not produce phase shifts or

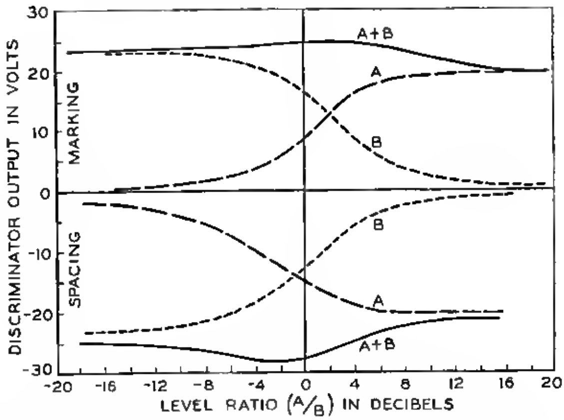

Fig. 36.—Diversity combination characteristic obtained by series addition of discriminator outputs—levels measured at output of 400 kc I.F. amplifier.

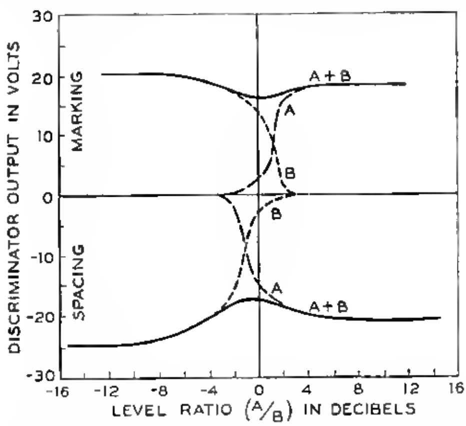

Fig. 37.—Diversity combination characteristic obtained by parallel addition of discriminator outputs—levels measured at output of 400 kc I.F. amplifier.

transmission delays as would actually exist over H.F. radio circuits the actual distortions shown by the curves are optimistic.

The ideal diversity selection circuit should theoretically give a signal-to-noise characteristic identical to that of a single channel under the signal-to-noise condition corresponding to the signal of the best momentary reception. It will be seen that the test results of Fig. 38 approach this limit within 2 or 3 db at a peak distortion of 20%. Part of this difference is

due to the dissimilar bandpass characteristics of the two channels of the experimental unit used for the tests and part due to the lack of an extremely sharp diversity selection. It should be pointed out that the conditions under which the theoretical maximum diversity signal-to-noise condition may be reached are very hard to obtain in practice. If the noise levels in the two

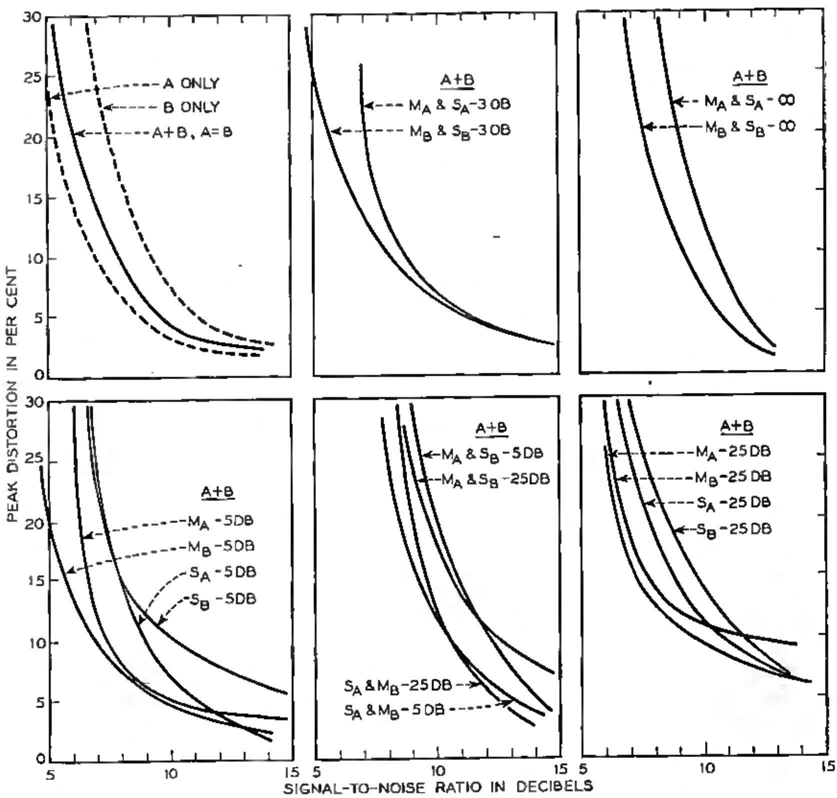

Fig. 38.—Peak distortion versus signal-to-noise ratio characteristics for dual-diversity operation with a common limiter. Signal-to-noise measured at output of 400 kc I.F. amplifier.

channels are not equal, and if the diversity selecting method does not at all times exclusively select the channel with the greater signal, the distortion characteristic will deteriorate accordingly. Because the AVC sensitivities of two radio receivers may differ considerably the noise levels cannot be maintained closely the same and usually no provision is made for determining the noise level except by ear. The slightly better diversity action which can theoretically be obtained is therefore felt to be of doubtful usefulness under actual operating conditions. The common limiter method has the

advantage of being simple in that the diversity action is obtained in the transmission circuits directly and no added switching circuits or adjustments are required. Tests of this type of diversity selection in the field have indicated a marked superiority over earlier FS terminal equipment.

In connection with the use of a common limiter care must be taken in the selection of the two-channel frequencies. Frequencies having nearly integral ratios such as 3:5 and 5:7 produce disturbing amplitude modulation of the demodulated signal. The frequencies should be chosen so as to avoid low integral ratios; then all amplitude modulations are negligible or easily filtered out. Where frequency drift is to be allowed for, the frequencies should be chosen so as not to approach a low integral ratio at any place in the expected drift range.

If the radio receivers associated with a space diversity FS system have automatic gain control it must be a common control so the receivers will change gain equally. The use of common AVC prevents overloading of the receivers as the received signal strength varies. If no common AVC is available the receivers should be operated in the manual gain-control condition.

Conclusions

General Comparison of FS and AM Carrier Telegraphy

The foregoing sections have compared the characteristics of AM and FS carrier telegraph transmission under various conditions. Whether or not FS would prove to be the preferable method for a specific communication use depends largely on the transmission medium and the quality of transmission desired. As regards frequency space requirements, both methods provide essentially the same signaling speed capability for a given bandwidth.

As to the ability to transmit through noise, FS has an advantage of 3 to 4 db at distortions approaching the failure point when equal bandwidths are compared. At lower distortions the advantage of FS is 6 db or more so that it is attractive in this respect for tandem operation of several telegraph sections where regeneration of signals is not practiced. When frequency space permits wider bands, with correspondingly increased frequency shifts, the signal-to-noise advantage of FS over AM increases for low noise levels. Wide band FS therefore provides a means of obtaining higher quality circuits if the noise level is not too great.

The AM method is basically less susceptible to frequency variations than is the FS method. However, as has been illustrated, frequency drift can be compensated for by d-c. elimination so as to make FS comparable to AM in this respect.

FS transmission is essentially immune from effects of non-selective level variation, even when extremely rapid, and in this characteristic displays its most outstanding advantage over AM.

Operation Over Wire Circuits

A wire circuit usually provides a transmission medium having a low noise level with slow and relatively small variations in attenuation. Such circuits, when equipped with suitable automatic gain control, allow stable operation with AM telegraphy and but little improvement could probably be obtained by using FS. The choice between AM and FS under such relatively ideal conditions becomes one of economic considerations of the terminal equipment and carrier supply. However, when FS is applied to multichannel systems the problem of interchannel interference requires attention. For wire circuits having high noise levels or sudden changes in attenuation the use of FS instead of AM provides considerable improvement and in severe cases the FS method may be a necessity for satisfactory operation. Wide band FS operation with its sharper breaking distortion-versus-noise-level characteristic gives a low value of rms-to-peak distortion which would be especially advantageous for tandem operation. However, the necessary frequency space for wide-band operation is not usually economically justified for wire line operation.

Operation Over Radio Circuits

For operation over radio circuits providing stable conditions similar to those on wire circuits the FS method does not show a great advantage over the AM method. In the case of long distance telegraphy in the H.F. range, however, FS shows a marked advantage over AM. This is because of the rapid fading and high noise conditions which commonly prevail in the H.F. region. The amount of rapid variation in marking level that an AM system can accommodate is less than the difference between marking and spacing levels that an FS system can tolerate. In the worst case of selective fading the level differences between the mark and space frequencies might approach values equal to the short time level swings of a single frequency, but in general would be less. A given condition of selective fading thus causes less distortion in an FS system than in an AM system. FS allows the use of narrow bands without much loss in signal quality in the presence of fading, whereas AM does not. FS therefore is essential for satisfactory operation of closely spaced narrow band H.F. radio channels. Where frequency space is not restricted and wider bands are used to permit considerable frequency drift, the improvement afforded by FS over AM is materially less. To obtain optimum results from an AM system, however, requires

more careful adjustment and more attention than does an FS system. This is partly due to the amplitude limiter in the FS system which results in a constant amplitude of signal from the discriminator and partly due to the fact that an FS signal is no more subject to noise interference during the spacing condition than during the marking condition. Therefore the operating point on the demodulated wave may be set and left for long intervals even though transmission conditions vary widely. This greater ease in maintaining good adjustment of the equipment probably accounts for some of the apparent improvement in changing from an AM to an FS system.

It should be noted that a system may fail either because of level variations well above the noise level or because of the signal becoming submerged in noise. If a system fails because it can accept only moderate level variations, an increase in transmitted power will provide no improvement since the level variations will remain the same as before. On the other hand, a system which can accept very wide variations in level will show improvement upon increasing transmitted power up to the point where no failures occur due to an unfavorable signal-to-noise ratio.

The over-all improvement obtained in changing from AM to FS radio telegraph is sometimes expressed as a ratio of transmitted powers required to give equivalent transmission results over the two systems. Such a ratio fluctuates widely depending upon the prevailing conditions. With little fading the improvement ratio will be mainly due to the better signal-to-noise obtained with FS and may be less than 5 db. Under severe fading conditions no amount of power may give good results with AM while FS may be satisfactory. Thus the power ratio would become infinite. By making a long-time comparison an average power ratio figure may be found which gives equal average error rates in the printed copy from each system. Such tests[7] between a triple space diversity AM system and a double space diversity FS system have indicated a power ratio of 11 db in favor of the latter when the error rate was 0.1 to 0.5 per cent.

When the two systems are thus made equal by adjustment of transmitted power, more errors due to the signal becoming submerged in noise occur in the FS system to compensate for a larger number of errors in the AM system due to rapid level changes. Often the reason for changing a radio telegraph system from AM to FS is to increase the reliability of the circuit and not just to save transmitted power. To insure a definite improvement in such cases the carrier level should not be decreased more than about 6 db.

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